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Changes in Climate Extremes and Catastrophic Events in the Mongolian Plateau from 1951 to 2012

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ABSTRACT

The spatiotemporal changes in 21 indices of extreme temperature and precipitation for the Mongolian Plateau from 1951 to 2012 were investigated on the basis of daily temperature and precipitation data from 70 meteorological stations. Changes in catastrophic events, such as droughts, floods, and snowstorms, were also investigated for the same period. The correlations between catastrophic events and the extreme indices were examined. The results show that the Mongolian Plateau experienced an asymmetric warming trend. Both the cold extremes and warm extremes showed greater warming at night than in the daytime. The spatial changes in significant trends showed a good homogeneity and consistency in Inner Mongolia. Changes in the precipitation extremes were not as obvious as those in the temperature extremes. The spatial distributions in changes of precipitation extremes were complex. A decreasing trend was shown for total precipitation from west to east as based on the spatial distribution of decadal trends. Drought was the most serious extreme disaster, and prolonged drought for longer than 3 yr occurred about every 7–11 yr. An increasing trend in the disaster area was apparent for flood events from 1951 to 2012. A decreasing trend was observed for the maximum depth of snowfall from 1951 to 2012, with a decreased average maximum depth of 10 mm from the 1990s.

1. Introduction

Significant global climate changes have been observed over the past century. As reported in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), warming of the climate system is unequivocal, and many of the observed changes have been unprecedented over different time scales (IPCC 2013). The report has also indicated that climate-related extreme events are increasing in frequency, severity, and duration (Selvey et al. 2014; Yilmaz et al. 2014). Scientists have gradually developed an understanding of the effects of global warming on water resources, agriculture, sea levels, ice sheets, and human health (Grassi et al. 2013; Yilmaz et al. 2014; Zhang et al. 2014). Extreme climate events are related closely to climate changes that have induced extremely hydrological and thermal anomalies (Chang et al. 2013; de Winter et al. 2012).

There is a significant consensus that the frequency and intensity of some extreme climate events are expected to increase worldwide over the next 50 years (Donat et al. 2013; García-Cueto et al. 2014). Climate change is likely to produce more extreme events (Tramblay et al. 2012), which could cause an increased probability of occurrence of events such as floods, droughts, heat waves, and snowstorms (García-Cueto et al. 2014; O'Gorman 2014). Changes in extreme climate events are crucial to society, the economy, and the environment because those events can always cause human losses and economic damages (Chang et al. 2013; Gregow et al. 2012). Meanwhile, extreme events are additional burden on health systems (Selvey et al. 2014) since climate-related change increases the demand for health care services (Casati et al. 2013; Rummukainen 2013).

More studies of regional changes in climatic extremes have been carried out than global-scale assessments. Many national and regional studies have been reported for China (Zhai et al. 2005; He et al. 2011; Cuo et al. 2013), North America (Aguilar et al. 2005; Williams

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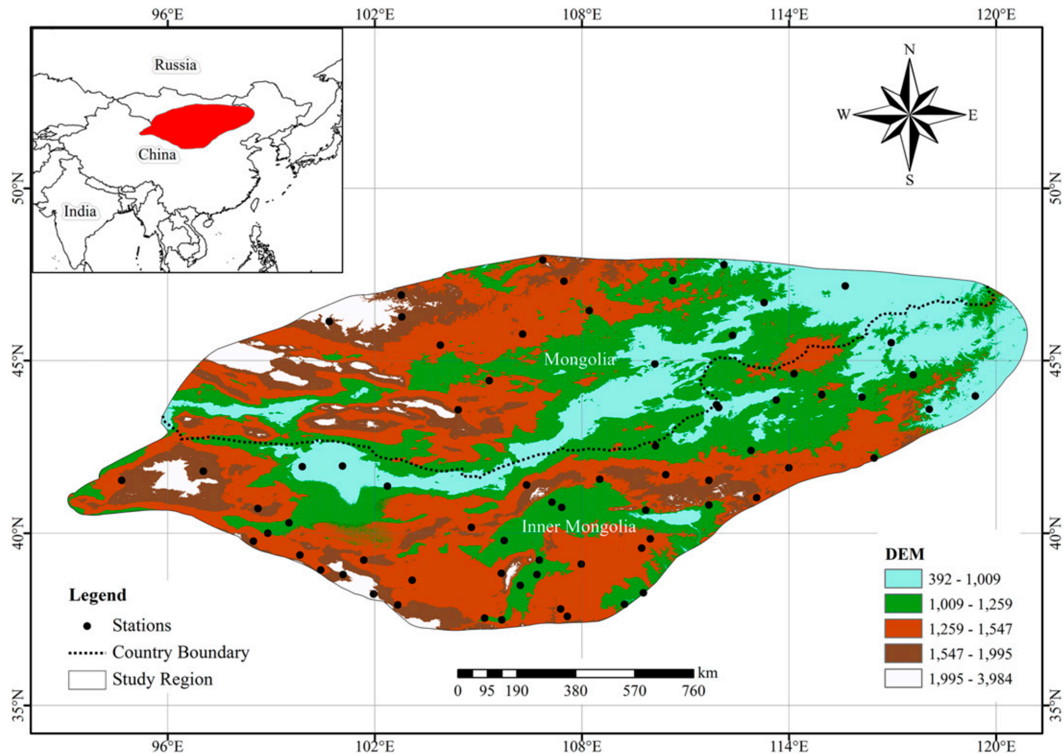

FIG. 1. Elevation map (m) of the Mongolian Plateau and the location of TNx meteorological stations.

et al. 2012), South America (Falvey and Garreaud 2009; Grimm 2011), Europe (Winkler 2009; van der Schrier et al. 2011), Australia (Plummer et al. 1999; Trewin 2013), and the Middle East (Zhang et al. 2005). There have been few studies of changes in climate extremes on the Mongolian Plateau in comparison with studies of other regions. Most of these studies considered only Inner Mongolia, which forms only a part of the Mongolian Plateau (Zhai and Pan 2003; Bai et al. 2006). There has also been little research on catastrophic events in this region. The aim of the work reported here was to analyze the variability and changes in frequency, intensity, and duration of extreme climate events in terms of temperature and precipitation extremes in the Mongolian Plateau region during 1951–2012. The spatial and temporal variability of the changes in temperature and precipitation extremes and in the occurrence of catastrophic events were also analyzed. The correlation relationship between catastrophic events and the indices of climate extremes was examined.

2. Materials and methods

a. Study area

The Mongolian Plateau is an East Asian inland plateau, surrounded by high-altitude mountains in the north and adjacent to the Gobi Desert in the south, which form the significant geographical boundaries of this region (Liu et al. 2013; Shi et al. 2010). In this region, the mountains are high in the west but low in the east; it is a basin, where Daxinganling lies to the east, the Sayan and Hentiy mountain ranges to the north, and the Yinshan mountain ranges to the south (Zhang et al. 2009). Furthermore, it is a spacious high plain with typical steppes and deserts that shape the geomorphology of the region. The plateau is occupied by Mongolia in the northwest and Inner Mongolia and China in the southeast (Fig. 1).

The Mongolian Plateau experiences a typical continental climate with low annual precipitation, frequent droughts, and windy periods during the winter and spring seasons (Zhang et al. 2009). The average temperature is −26°C in January and 17°C in July. The annual average precipitation in most regions is $<$200 mm, although it may reach 400 mm or higher in the eastern, northeastern, or northern mountainous areas (Zhang et al. 2009). More than 70% of the annual precipitation occurs from June to August and the interannual variability in precipitation is striking. There are fewer than 10 people per square kilometer in this sparsely populated area and the major production activity is animal husbandry. There has been fast growth in the number of livestock since the 1950s and, as the frequency of extreme climate events has increased, there

TABLE 1. Definition of the temperature and precipitation indices used in this study. (Abbreviations are as follows: TX = daily maximum temperature; TN = daily minimum temperature; PRCP = precipitation; RR = daily precipitation. A wet day is defined when RR ≥ 1 mm, and a dry day is when RR < 1 mm.)

Index	Indicator name	Definition	Units
Temperature			
TXx	Max Tmax	Annual max value of daily max temperature	°C
TNx	Max Tmin	Annual max value of daily min temperature	°C
TXn	Min Tmax	Annual min value of daily max temperature	°C
TNn	Min Tmin	Annual min value of daily min temperature	°C
TN10p	Cool nights	Percentage of days when TN < 10th percentile	days
TX10p	Cool days	Percentage of days when TX < 10th percentile	days
TN90p	Warm nights	Percentage of days when TN > 90th percentile	days
TX90p	Warm days	Percentage of days when TX > 90th percentile	days
WSDI	Warm-spell-duration indicator	Annual count of days with at least 6 consecutive days when TX > 90th percentile	days
CSDI	Cold-spell-duration indicator	Annual count of days with at least 6 consecutive days when TN < 10th percentile	days
DTR	Diurnal temperature range	Annual mean difference between TX and TN	°C
Precipitation			
RX1day	Max 1-day precipitation amount	Annual max 1-day precipitation	mm
RX5day	Max 5-day precipitation amount	Annual max consecutive 5-day precipitation	mm
SDII	Simple daily intensity index	Avg PRCP on wet days in the year	mm day^{-1}
R10	No. of heavy precipitation days	Annual count of days when PRCP ≥ 10mm	days
R20	No. of very heavy precipitation days	Annual count of days when PRCP ≥ 20mm	days
CDD	Consecutive dry days	Max no. of consecutive dry days	days
CWD	Consecutive wet days	Max no. of consecutive wet days	days
R95p	Very wet days	Annual total PRCP when RR > 95th percentile	mm
R99p	Extremely wet days	Annual total PRCP when RR > 99th percentile	mm
PRCPTOT	Annual total wet-day precipitation	Annual total PRCP from wet days	mm

have been increasing losses of livestock due to extreme climate events.

b. *Data and methods*

The daily precipitation, daily temperature, and data on meteorological disasters from 1951 to 2012 were used to calculate and analyze the extreme indices and catastrophic events, which were provided by China Meteorological Data Sharing Service System (http://cdc.nmic.cn/home.do) and the National Climatic Data Center, U.S. Department of Commerce (http://www.ncdc.noaa.gov/). The extreme disaster events data are from the Dictionary of Meteorological Disasters in China Series (Shen 2008), China Meteorological Data Sharing Service System, and *Bulletin of Flood and Drought Disasters in China* (http://www.mwr.gov.cn/). Figure 1 shows the distribution of meteorological stations on the Mongolian Plateau. There are 84 meteorological stations on the Mongolian Plateau, of which 53 are meteorological stations in China, and most of them began operation in the 1950s. Fourteen meteorological stations in Mongolia were excluded due to data quality problems. Detailed information about the stations is provided in appendix Table A1.

These extreme indices are calculated using RClimDex, a software package developed by the Climate Research Branch of the Meteorological Service of Canada on behalf of the Expert Team on Climate Change Detection, Monitoring and Indices (Zhang et al. 2005, 2011). RClimDex calculates 16 temperature and 11 precipitation indices that are defined by the World Meteorological Organization Working Group on Climate Change Detection. This suite of indices was used to examine changes in extremes in five areas of the world where regional climate change workshops were held (Aguilar et al. 2005; Haylock et al. 2006; Klein Tank et al. 2005; New et al. 2006; Vincent et al. 2005; Zhang et al. 2005), and one global analysis incorporated the indices calculated at the regional workshops (Alexander et al. 2006). In this study, indices mostly relevant to this study area were examined and a final selection of 11 temperature and 10 precipitation indices was selected (Table 1). Before calculating these indices, it is vital to carry out a data quality control procedure and a homogeneity test. The main purpose of this data quality control procedure is to identify the errors caused by data processing because erroneous outliers can seriously affect extreme trends. Data quality control is performed using RClimDex and data homogeneity is assessed using RHtest developed by X. L. Wang at the Climate Research Branch of the Meteorological Service of Canada (Wang 2003, 2008). This program is capable of identifying multiple step changes at documented or undocumented changepoints (Zhang et al. 2005).

Linear trends for these series of indices were calculated using a nonparametric slope estimator based on Kendall's tau coefficient (Sen 1968). A linear trend was considered to be statistically significant if it was significant at the 5% level. Trends for both individual stations and the region as a whole are calculated. The regional series are obtained from individual station anomaly series using the arithmetic average method. For the precipitation indices, in order to avoid the average series being dominated by those stations with high precipitation, the anomaly series were standardized by dividing them by the station standard deviation (New et al. 2006).

TABLE 2. Trends of annual regional indices and number of stations with positive (P) and negative (N) trends. Values for trends significant at the 5% level are shown in boldface type.

Index	Slope	Positive	Significant-P	Negative	Significant-N
TXx	**0.014**	68	50	2	1
TNx	**0.022**	70	62	0	0
TXn	**0.018**	53	45	17	4
TNn	**0.036**	56	47	14	7
TN10p	**−0.329**	6	3	64	62
TX10p	**−0.115**	1	0	69	60
TN90p	**0.310**	69	63	1	0
TX90p	**0.127**	68	63	2	0
WSDI	**−0.112**	67	30	3	1
CSDI	**−0.062**	15	1	55	7
DTR	**−0.018**	16	10	54	51
RX1day	−0.037	31	12	39	9
RX5day	−0.008	30	6	40	15
SDII	0.005	35	9	35	12
R10	−0.024	38	11	32	7
R20	−0.009	27	5	43	9
CDD	**0.176**	30	13	40	13
CWD	**−0.006**	33	10	37	10
R95p	−0.307	27	9	43	13
R99p	−0.108	31	3	39	2
PRCPTOT	**−0.772**	30	8	40	11

3. Results and analysis

a. *Temperature extremes*

1) COLD EXTREMES

The cold extremes indices include the percentile-based temperature indices of cool days (TX10p) and cool nights (TN10p), cold-spell-duration indicator (CSDI), and the absolute temperature indices of minimum daily maximum temperature (TXn; i.e., coldest days) and minimum daily minimum temperature (TNn; i.e., coldest nights). A total of 99% of the stations had negative trends and 86% had significant negative trends in the TX10p index (Table 2). Twelve stations decreased by over 2 days per decade and 70% of the stations decreased by over 1 day per decade. In addition, every station in the eastern part of Inner Mongolia decreased by more than 1.5 days per decade, whereas smaller decreasing general trends were mainly found in Mongolia and western part of Inner Mongolia (Fig. 2). Similar negative trends also were seen in the TN10p index; 91% of the stations had negative trends and 89% had significant negative trends (Table 2). The spatial distributions of the general trends for TN10p were similar to those for TX10p. However, the size of the trends for TN10p was larger than for TX10p (Fig. 3) and 67% of the stations decreased by over 2 days in decadal trends, including 17 stations that decreased by over 5 days (Fig. 2). Regionally, a decreasing trend was apparent since 1951 for these percentile-based indices. More specifically, there was a continuing decreasing trend from the end of the 1970s (Fig. 3). However, for TN10p both the magnitude and the number of stations with significant trends were larger than those for TX10p (Table 2). The slopes of the trends were almost 2 times larger than those for the latter (−3.29 and −1.15 days decade^{-1}, respectively). That is, the warming of night is more pronounced than day, showing an asymmetric warming characteristic.

For the CSDI, 79% of the stations had negative trends, but significant negative trends were not found for most stations due to the higher variance of this index. At the regional scale CSDI also showed a decreasing trend although there were several abrupt risings before 1990 (Fig. 3). In contrast, TXn and TNn showed increasing trends at 80% and 81% of stations and the significant positive trends were 64% and 69%, respectively (Table 2). It should be noted that the Inner Mongolia showed a much higher degree of coherence than Mongolia, especially for index of TXn (Fig. 2). These two indices showed a similar pattern with an obvious increasing trend, despite a sharp drop in 1950s followed by sharp increases in 1960 and 1970 (Fig. 3). Similar to percentile-based indices but in opposite direction, TNn was larger than TXn in both magnitude and the number of stations with significant trends. The regional trends in TNn and TXn were 0.36° and 0.18°C decade^{-1}. This denotes that it was warming faster at night than in the daytime.

In brief, the changes of cold extremes showed that there had been significant decreases in the number of cool nights as well as increases of minimum daily minimum temperature. In addition, the cold-spell duration was down. All of these indicated that the cold extremes

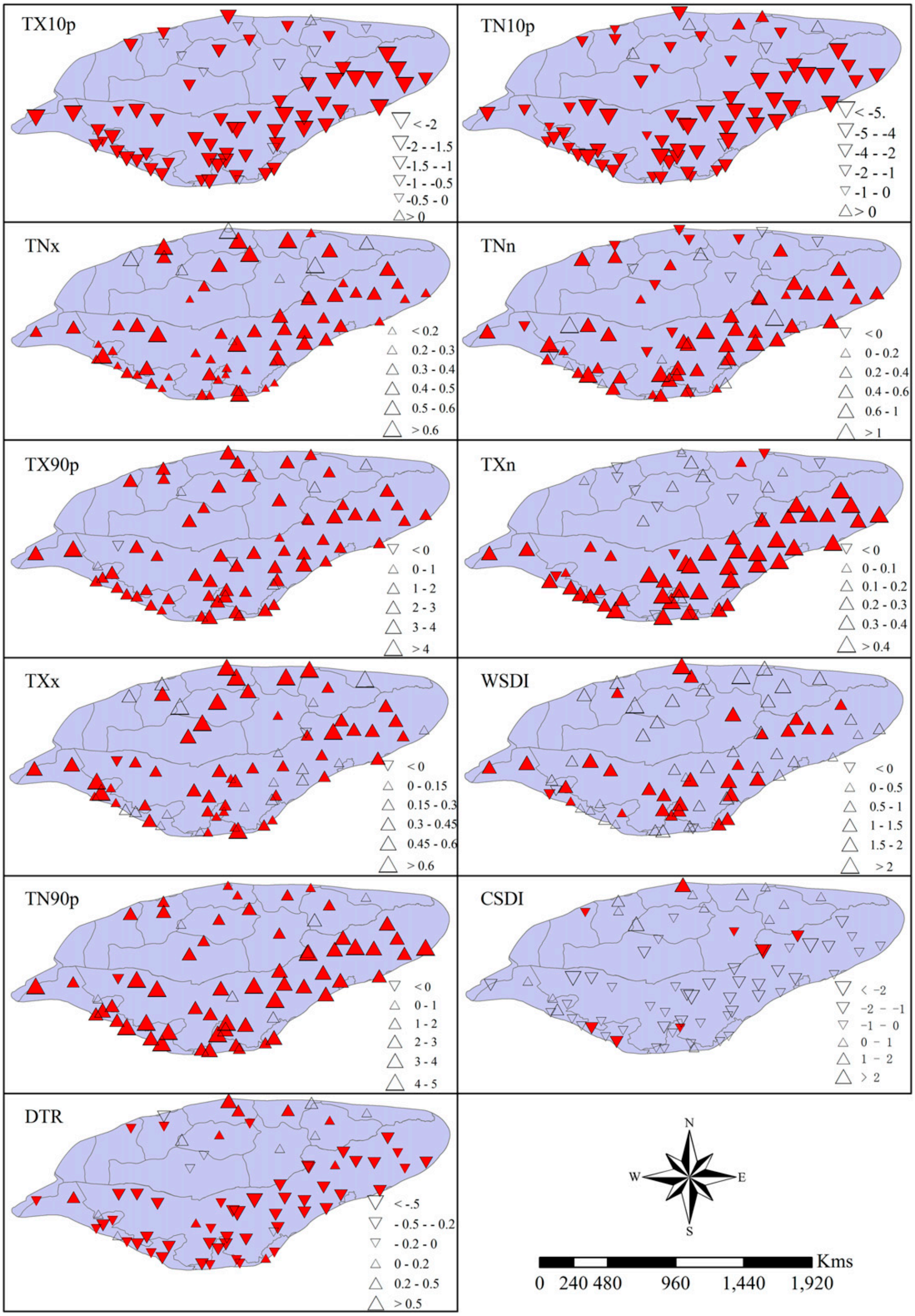

FIG. 2. Spatial distribution of decadal trends for the different indices of temperature extremes. Upward (downward) triangles represent positive (negative) trends. Solid red triangles indicate trends significant at the 5% level.

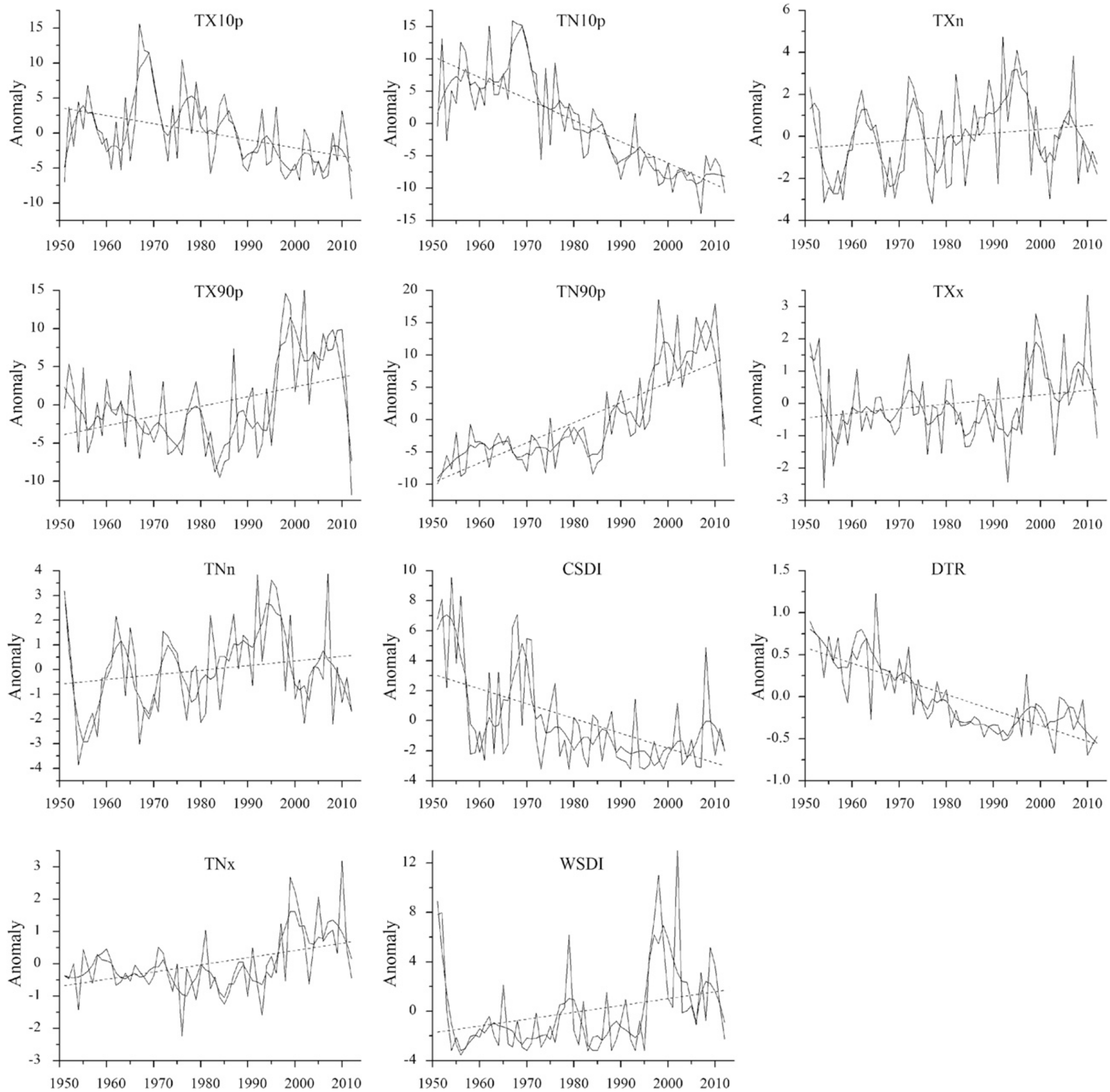

FIG. 3. Regional annual anomaly series for indices of temperature extremes. The dashed line is the linear trend, and the smoother solid line is the 9-yr average.

were weakening both in magnitude and frequency, and greater warming occurred at night than in the daytime.

2) Warm extremes

The warm extremes include the percentile-based temperature indices of warm days (TX90p) and warm nights (TN90p), the warm-spell-duration indicator (WSDI), and the absolute temperature indices of maximum daily maximum temperature (TXx; i.e., the warmest daytime) and maximum daily minimum temperature (TNx; i.e., the warmest nighttime). The TX90p index generally showed positive trends although it experienced a trend of ascending after descending (Fig. 3), and it exhibited good spatial coherence over the whole region (Fig. 2). Almost all stations (97%) had a positive trend and the percentage of stations with significant trends (90%) was much greater than for TX10p, indicating that increasing trends in the number of warm days are much more pronounced than the decreases in the number of cold days. For the TN90p, 99% of the stations had positive trends and 90% had significant trends. The stations with increasing trends were spatially evenly distributed over the whole region (Fig. 2). From the perspective of regional scale, a downward trend was apparent for TX90p until the 1980s, and then changed into a sharply increasing trend. The TN90p trends were different from the trends in TX90p, with subtle fluctuations until the mid-1980s and then a change into a sharply increasing trend (Fig. 3). This also showed a faster increase at night than in the daytime, especially from the 1980s, with the slopes of the upward trend for nighttime twice that for the daytime. As for the WSDI, although more stations showed positive trends (96%), few significant upward trends occurred in the region as a whole. The overall impression was a dominance of positive trends in TXx and TNx; the percentages of stations with positive trends were 97% and 100% (significant positive trends 72% and 89%), respectively. The largest increase of both indices mainly occurred in the northern part of Mongolia (Fig. 2). The regional increasing trends in TXx and TNx were 0.14° and 0.22°C decade^{-1}. Thus, it can be concluded that the warming mainly occurred in the nighttime.

3) OTHER EXTREME INDICES AND CONTRASTS

Unlike the temperature indices discussed in the preceding sections, the diurnal temperature range (DTR) does fall into traditional categories, but changes in the DTR could have significant impacts on society (Wang et al. 2013). As stated in the conclusion of Li et al. (2012), there has been a decreasing trend of DTR due to the rapid increase of the minimum temperature in recent decades. This study also found a downward trend of DTR in the entire region (Fig. 3) and around 73% of the stations experienced a significant positive trend (Table 2). Larger DTR diminished areas were mainly located in the southern area of Inner Mongolia, specifically the desert areas (Fig. 2). As mentioned before, larger warming was found in measures of cool nights (TN10p) and the coldest nights (TNn), which resulted in a decrease of DTR at a rate of −0.18°C decade^{-1}. This trend indicates an asymmetric warming, which confirms the analysis of the previous sections.

b. Precipitation extremes

In contrast with the temperature extremes, the significance of changes in precipitation extremes during 1951–2012 was low on the Mongolian Plateau. Overall, only consecutive dry days (CDD), consecutive wet days (CWD), and annual total wet day precipitation (PRCPTOT) had a significant trend due to the larger heterogeneity of precipitation. For these three indices, 59%, 53%, and 57% of stations had decreasing trends (Table 2) and most of them were located in Inner Mongolia (Fig. 4).

PRCPTOT showed larger decreasing magnitudes and the regional trend was −7.72 mm decade^{-1}, with big fluctuations from 1951 to 1980, which subsequently changed to a more gradual downward trend from the 1980s (Fig. 5). About 43% of stations had increasing trends, larger magnitudes of which mostly occurred in Mongolia. It was revealed that Mongolia was drier than Inner Mongolia.

The maximum 1-day precipitation (RX1day) and maximum 5-day (RX5day) precipitation showed nonsignificant downward regional trends and the percentages of stations with negative trends were 56% and 57%, respectively. Only a few stations had a significant negative trend over the whole region and the spatial distributions of these two indices were very similar (Fig. 4). Regionally, they experienced similar up–down cycles (Fig. 5). In a similar manner to the RX1day and RX5day, the very wet days (R95p) and extremely wet days (R99p) also showed a mainly downward trend, and the percentages of stations with negative trends were 62% and 54%, respectively. The spatial distribution of stations with significant negative trends for R95p was similar to those for the RX5day. All but five stations had no significant trend for the R99p.

The average precipitation on wet days (SDII) had a downward trend and half of the stations had negative trends (Table 2). Stations with significant decreasing trend were all in Inner Mongolia while stations with larger decreasing trend magnitudes were mainly in Mongolia (Fig. 4). The decrease of heavy precipitation days (R10mm) and heavier precipitation days (R20mm) was almost common with nonsignificant downward trend (Fig. 5) although some stations showed a significant increasing trend in the western and central parts of Inner Mongolia (Fig. 4). The decreasing trend magnitudes of both indices in Mongolia were larger than in Inner Mongolia, which indicated fewer heavy precipitation extreme events in Mongolia than in Inner Mongolia. These two indices showed larger spatial heterogeneity.

Although the trends in the consecutive dry days (CDD) index were negative in more than half of the stations (57%), most of the trends were nonsignificant and the regional trend was significantly positive (1.76 days decade^{-1}). The consecutive wet days (CWD) index exhibited a slightly decreasing trend (−0.06 days decade^{-1}) although the stations with positive trends were comparable with those having negative trends (33/37; Table 2). These characteristics indicated that the region as a whole experienced a drier climate.

c. Catastrophic extreme events

This study focused on the extreme disaster events of droughts, floods, and snowstorms on the Mongolian

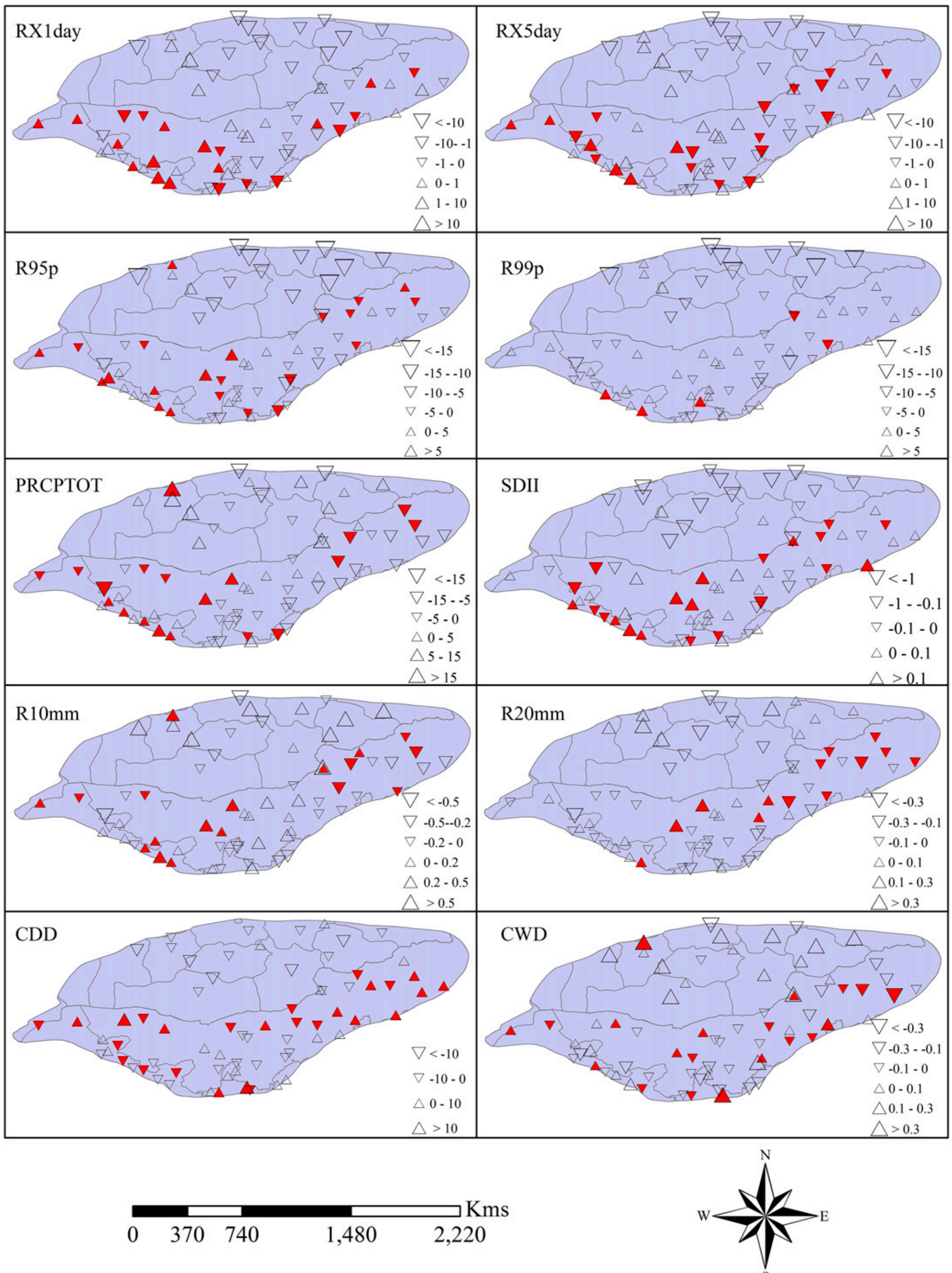

FIG. 4. As in Fig. 2, but for precipitation.

Plateau. Drought was the most serious extreme disaster on the Mongolian Plateau. Figure 6b shows that the disaster area affected by drought was dominated by an increasing trend from 1951 to 2012, following a similar pattern to that seen for the CDD index (Fig. 6a; Inner Mongolia annual series). There have been 35 years with various degrees of regional drought (≥1 million ha) in Inner Mongolia over the past half century; in particular, most areas have experienced time intervals with droughts lasting no less than 3 yr, including 1950–53

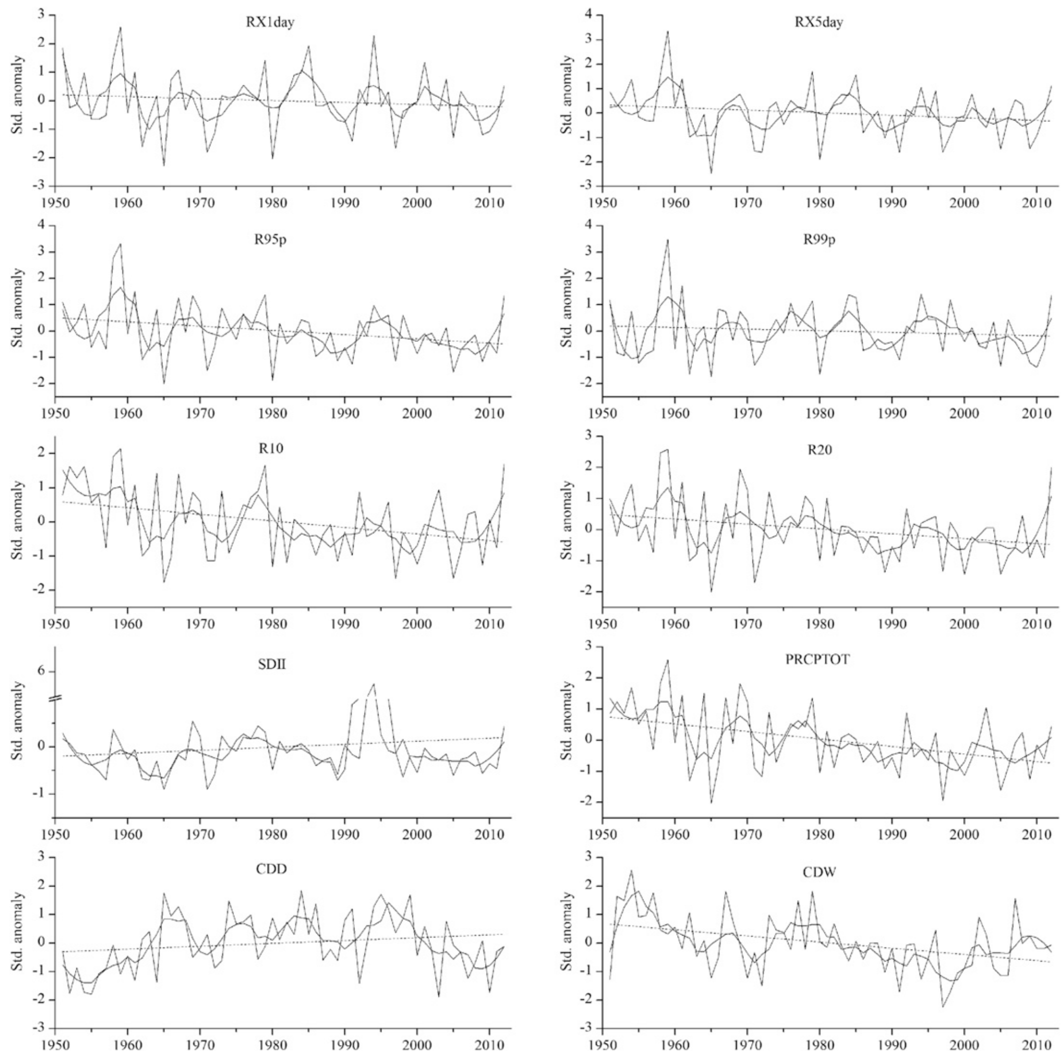

FIG. 5. As in Fig. 3, but for precipitation.

(4-yr drought), 1960–62 (3-yr drought), 1971–73 (3-yr drought), 1980–82 (3-yr drought), 1991–94 (4-yr drought), 1999–2004 (6-yr drought), and 2006–09 (4-yr drought). Droughts lasting more than 3 yr occurred about every 7–11 yr.

Drought, especially prolonged drought, can have devastating impacts on agriculture, animal husbandry, industry, and water resources. For example, continuing drought in 1980–82 resulted in a grain loss of 2.8×10^6 tons and a 7.2×10^5 loss of cattle with farmers fleeing and begging as a result of insufficient food provision. In addition, herders suffered from limited forage to grazing (Shen 2008).

Although a dry and rainless climate is the main characteristic of the Mongolian Plateau, extreme rainstorms covering large areas can occur under certain conditions. An increasing trend for the disaster areas affected by floods was dominant during 1951–2012 (Fig. 6c). Disaster events associated with local heavy rainfall often occur as a result of the particular thermodynamic and dynamic conditions present at the edge of the East Asian monsoon (Zhang et al. 2009). This is because 70% of the annual precipitation is concentrated in the period from June to August and much of this precipitation falls in heavy rainstorms. Examples of extreme heavy rainfall include 520 mm in the suburb of Hohhot City (5 July 1974); 500 mm in Wulate Houqi, Bayan Joy City (15 August 1975); over 400 mm in Siziwang Banner (30 June 1981); and the rainstorm in southern Erdos City on the night of 1 August 1977. This last event had the highest recorded daily precipitation in China, reaching 1400 mm in 10 h.

Generally, the greater the snowfall is, the thicker is the snow cover. A long duration of snow cover of a

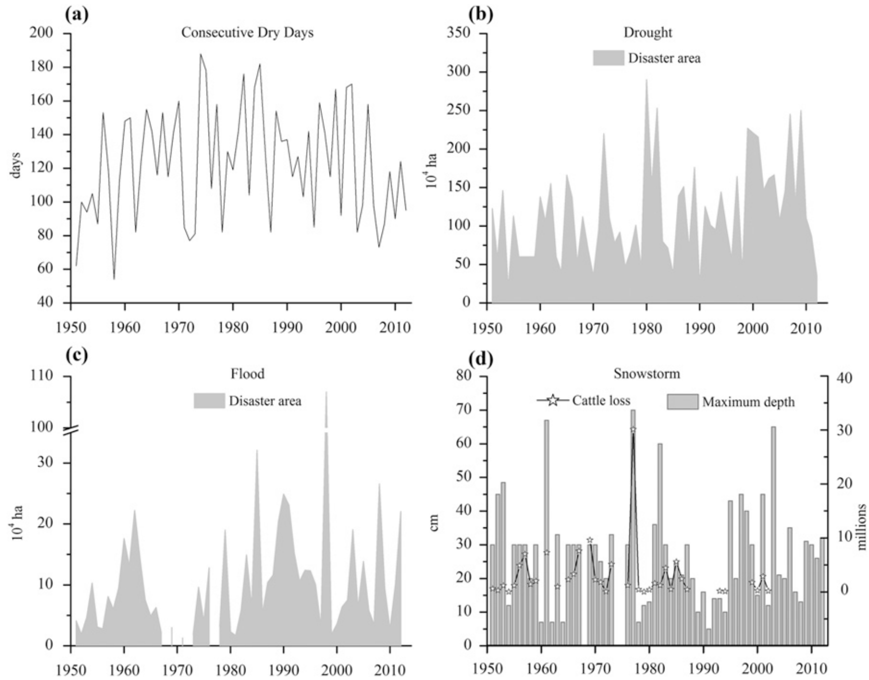

FIG. 6. Regional annual series for extremes disaster events in Inner Mongolia: (a) consecutive dry days, (b) drought, (c) flood, and (d) snowstorms; the curve in (d) indicates cattle loss.

certain depth will lead to a disaster event. When the snow cover depth is ≥7 cm and the stable maximum temperature is less than or equal to −7°C, the ground temperature remains below 0°C and the snow is difficult to melt (Shen 2008). Snowfall begins in September and stops in May of the following year. The duration of snowfall is more than 9 months. Snow cover lasts from mid-October to early May of the following year. The average temperature in November is below −7°C in pastureland and this temperature lasts until early March. Heavy snow and snowstorms during this period are prone to cause snowstorm disaster events. As a result of the warming trend of temperature extremes and the decreasing trend of annual total wet day precipitation (PRCPTOT), a decreasing trend was seen for the maximum depth of snow on the Mongolian Plateau from 1951 to 2012 (Fig. 6d). A change in the trend occurred in the 1980s and the average maximum depth was 30 mm in 1951–90. A decreasing trend of cattle loss due to snowstorms was apparent from 1951 to 2012. The worst snowstorm disaster occurred in 1977, the worst recorded since the beginning of the last century, with a maximum depth of snowfall of >70 cm and, in some places, >1 m. More than 10 million cattle were affected by the snowstorm disaster and over 3 million died. With the growth in the social economy, the impact of snowstorm disasters was lower from the 1980s onward. The impact further weakened after 2003, when the Grain for Green Project was implemented.

d. Correlation relationship

In our analysis, the extreme indices showed changes in the overall regional trends, but changes in catastrophic extreme events have occurred on smaller regional or local scales. The extreme indices for this particular station corresponded well with these extreme disaster events. The CDD was one of the most significant extreme indices in terms of drought and our analysis showed that this index indicated arid conditions in the local area. We used the drought that occurred at the Balinzuoqi station (54027), which has relatively complete disaster data, as an example to analyze the correlation relationship between the extreme indices and extreme disaster events (Fig. 7). The CDD was a good indication of the changes in drought conditions at the station, especially the change in overall trends. An exception was the extreme drought that occurred in the southern parts of Chifeng City in 1981; the Balinzuoqi station is in the north of Inner Mongolia.

4. Discussion

Changes of climate extremes over the Mongolian Plateau are similar to those of other areas (Table 3), but the indices of precipitation are different to some degree.

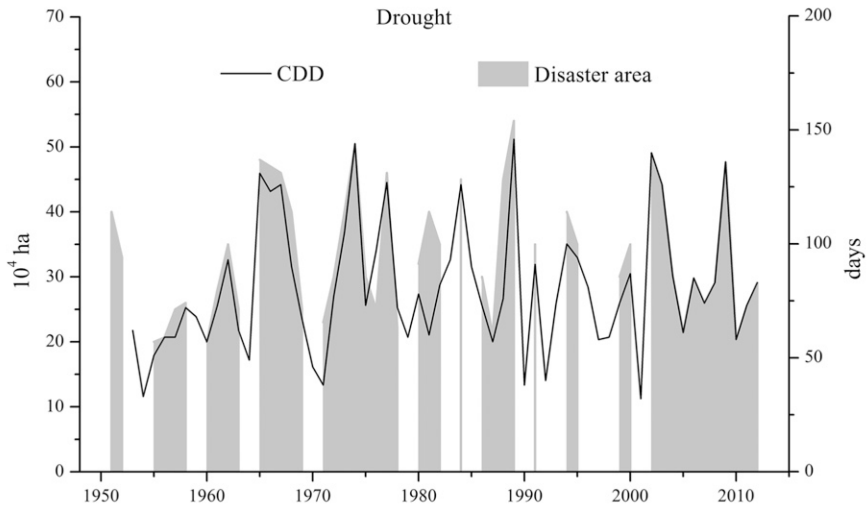

FIG. 7. Correlation relationship for extreme indices (CDD; solid line) and extreme disaster events (shading) of Balinzuoqi (54027).

The trends of all precipitation extremes indices but CDD were decreasing. These are different from elsewhere either in magnitude or in the direction of trend. At the regional scale, decreasing trends of CWD and PRCPTOT are consistent with the findings by Choi et al. (2009) for the Asia–Pacific network region (-0.01 days decade^{-1} and -4.4 mm decade^{-1}, respectively). It implies that the Mongolian Plateau experienced a drier and even rainless climate. This is also evidenced by the significant increasing trend of CDD (1.76 days decade^{-1}). This is different from other areas such as the Tibetan Plateau and southwestern China. However, the Mongolian Plateau as a traditional area of farming and agricultural activity would suffer particularly from extreme drought events.

All the temperature extremes (cold extremes and warm extremes) showed regional warming trends on Mongolian Plateau from 1951 to 2012. This was similar to the increasing trends since the 1950s in both the maximum and minimum air temperature extremes in eastern Asia, northern Africa, and some regions of South America (Donat et al. 2013). The widespread significant changes in almost all the temperature indices in this study area agree with the generally expected

TABLE 3. Trends per decade of temperature and precipitation extremes in the Mongolian Plateau and other areas.

Index	Mongolian Plateau 1951–2012	Eastern and central Tibetan Plateau 1961–2005	Southwestern China 1961–2008	Asia–Pacific network region 1955–2007	Global 1951–2011
TX10p	−1.15	−0.85	−0.13	−3.3	−0.86
TN10p	−3.29	−2.38	−0.37	−6.4	−1.26
TXn	0.18	0.3	0.13	0.3	0.28
TNn	0.36	0.69	0.29	0.3	0.45
TX90p	1.27	1.26	0.22	3.9	1.14
TN90p	3.1	1.58	0.36	5.4	1.79
TXx	0.14	0.28	0.11	0.1	0.11
TNx	0.22	0.25	0.17	0.2	0.12
DTR	−0.18	−0.2	−0.18	−0.1	−0.09
RX1day	−0.37	0.27	0.05	0.45	0.04
RX5day	−0.08	−0.08	0.03	0.82	−0.31
R95p	−3.07	1.28	0.04	2.3	1.98
R99p	−1.08	1.09	0.05	1.64	1.42
R10	−0.24	0.23	0	−0.1	−0.07
PRCP	−7.72	6.66	0.03	−1.24	0.23
SDII	0.05	0.03	0.03	0.09	−0.07
CDD	1.76	−4.64	−0.05	0	−1.66
CWD	−0.06	−0.07	−0.08	−0.01	0.02
Sources	This study	You et al. (2008)	Li et al. (2012)	Choi et al. (2009)	Donat et al. (2013)

TABLE A1. The details of meteorological stations.

WMO No.	Name	Period	Lat (°N)	Lon (°E)
50915	East Wuzhumuqinqi	1955–2012	45.52	116.97
52267	Mesozoic-Cenozoic	1959–2012	41.95	101.07
52313	Hongliuhe	1952–2012	41.53	94.67
52323	Mazongshan	1957–2012	41.80	97.03
52343	Jihede	1958–86	41.93	99.90
52378	Guaizihu	1959–2012	41.37	102.37
52441	Wutonggou	1965–88	40.72	98.62
52446	Dingxin	1955–2012	40.30	99.52
52447	Jinta	1989–2012	40.00	98.90
52495	Bayinmaodao	1957–2012	40.17	104.80
52533	Jiuquan	1951–2012	39.77	98.48
52546	Gaotai	1952–2012	39.37	99.83
52576	Alashanzuoqi	1959–2012	39.22	101.68
52652	Zhangye	1951–2012	38.93	100.43
52661	Shandan	1952–2012	38.80	101.08
52674	Yongchang	1958–2012	38.23	101.97
52679	Wuwei	1951–2012	37.92	102.67
52681	Minqin	1953–2012	38.63	103.08
53068	Erenhot	1955–2012	43.65	111.97
53083	Narenbaolige	1957–2012	44.62	114.15
53149	Mandula	1957–2012	42.53	110.13
53192	Abagaqi	1952–2012	44.02	114.95
53195	Sunitezuoqi	1955–2012	43.87	113.63
53231	Hailisu	1970–2012	41.40	106.40
53276	Zhurihe	1952–2012	42.40	112.90
53336	Wulatezhongqi	1954–2012	41.57	108.52
53352	Daerhanlianheqi	1953–2012	41.70	110.43
53362	Siziwang Banner	1959–2012	41.53	111.68
53391	Huade	1952–2012	41.90	114.00
53420	Hangjinhouqi	1954–2012	40.90	107.13
53446	Baotou	1951–2012	40.67	109.85
53463	Hohhot	1951–2012	40.82	111.68
53480	Jining	1954–2012	41.03	113.07
53502	Jilantai	1955–2012	39.78	105.75
53513	Linhe	1956–2012	40.75	107.42
53519	Huinong	1957–2012	39.22	106.77
53529	Etuokeqi	1954–2012	39.10	107.98
53543	Dongsheng	1956–2012	39.83	109.98
53545	Ejin Horo Banner	1958–2012	39.57	109.73
53602	Alxa Left Banner	1952–2012	38.83	105.67
53614	Yinchuan	1951–2012	38.48	106.22
53615	Taole	1959–2012	38.80	106.70
53646	Yulin	1951–2012	38.27	109.78
53704	Zhongwei	1959–2012	37.53	105.18
53705	Zhongning	1953–2012	37.48	105.68
53723	Yanchi	1954–2012	37.80	107.38
53725	Dingbian	1989–2012	37.58	107.58
53740	Hengshan	1954–2012	37.93	109.23
54012	West Ujimqin Banner	1954–2012	44.58	117.60
54027	Balinzuoqi	1953–2012	43.98	119.40
54102	Xilin Hot	1952–2012	43.95	116.12
54115	Linxi	1952–2012	43.60	118.07
54208	Duolun	1952–2012	42.18	116.47
442850	Khujirt	1947–2012	46.90	102.77
442870	Bayankhongor	1962–2012	46.13	100.68
442880	Arvaikheer	1940–2012	46.27	102.78
442920	Ulaanbaatar	1936–2012	47.92	106.87
442940	Maant	1955–2012	47.30	107.48
442980	Choir	1949–2012	46.45	108.22
443020	Bayan-Ovoo	1961–2012	47.78	112.12
443040	Undurkhaan	1936–2012	47.32	110.63
443050	Baruun-Urt	1960–2012	46.68	113.28
443140	Matad	1938–2012	47.17	115.63
443360	Saikhan-ovoo	1966–2012	45.45	103.90
443410	Mandalgobi	1944–2012	45.77	106.28
443470	Tsogt-ovoo	1962–2012	44.42	105.32
443520	Bayandelger	1938–2012	45.73	112.37
443540	Sainshand	1936–2012	44.90	110.12
443580	Zamiin-uud	1955–2012	43.73	111.90
443730	Dalanzadgad	1936–2012	43.58	104.42

results of a warming world (Donat et al. 2013), with decreases in cold extremes and increases in warm extremes. Both the cold extremes and warm extremes showed greater warming at nighttime (TN10p, TN90p, TNx, and TNn) than in the daytime (TX10p, TX90p, TXx, and TXn). This was also confirmed by a decrease in the DTR index, and the trend of the regional annual series is $-0.18°C\,decade^{-1}$. Similar results were observed during 1960–2000 in central and southern Asia ($-0.12°C\,decade^{-1}$) (Klein Tank et al. 2005). This indicates that the warming was an asymmetric process, of which the forcing effect is important to the terrestrial ecosystem (Peng et al. 2013). The changing trends, especially the significant changing trends, display better homogeneity and consistency in Inner Mongolia than in the Mongolian Plateau as a whole.

Drought was the most serious extreme disaster event, as the Mongolian Plateau experiences a typical continental climate with low annual precipitation (Zhang et al. 2009). The disaster area affected by drought shows an upward trend ($1.12 \times 10^4\,ha\,yr^{-1}$; confidence level 90%) between 1951 and 2012. This was confirmed by the changing trend of the CDD index. There were particular intervals of prolonged drought no less than 3 yr in duration in most areas (e.g., 1951–53, 1960–62, 1971–73, 1980–82, 1991–94, 1999–2004, and 2006–09). Prolonged droughts occurred about every 7–11 yr, and recent decade is in the state of extreme drought, showing a warmer climate condition. Despite low annual precipitation, more than 70% of the annual precipitation is concentrated in June to August and much of this precipitation falls in heavy rainstorms. For example, recent reports included heavy rainfall (rainstorm and hail) of 71 mm in Dongsheng, Ordos City (30 June 2013), with 19 people killed and 979 trapped, and a large number of vehicles were overwhelmed or smashed by hail (http://www.chinanews.com/gn/2013/07-02/4992367.shtml). A slight increasing trend ($0.11 \times 10^4\,ha\,yr^{-1}$; confidence level

90%) for the disaster area affected by floods was observed with from 1951 to 2012. Snowstorms are typical natural disasters in the Mongolian Plateau. Because of the downward trend of PRCPTOT, the maximum depth of snow has decreased 0.5 cm decade^{-1} from 1951 to 2012.

These extreme climate indices indicate a change in the extremes of the overall regional trends and there was a good correlation with a few catastrophic extreme events that occurred over the whole region. However, these extreme disaster events frequently occurred on a local scale. The extreme indices for a particular station were not always well correlated with the extreme disaster events over the whole region. The climate extremes are the main cause of catastrophic extreme events and thus further research is needed to investigate the inherent relationships in changes in the occurrence of extreme temperature and precipitation on the Mongolian Plateau.

5. Summary

With the help of a suite of universal descriptive indices, a better understanding of observed changes in temperature and precipitation extremes is gained for the Mongolian Plateau during 1951–2012. In addition to trends of extreme climate, some time series of catastrophic events are also analyzed.

Changes in night extremes (TN10p, TN90p, TNx, and TNn) were larger than for day extremes (TX10p, TX90p, TXx, and TXn), and stations with significant trends of all night indices were located throughout the whole region. This trend indicated an asymmetric warming characteristic in the Mongolian Plateau. Meanwhile, the observed decrease in the DTR indicated both the cold extremes and warm extremes show greater trend magnitudes at night than in the day.

Consistent patterns and significance of changes in precipitation extremes detected for the majority of precipitation indices were low in the Mongolian Plateau. These indices with a significant change trend are CDD, CWD, and PRCPTOT. The decreasing trends of CWD–PRCPTOT and increasing trend of CDD indicate a drying trend, which could indicate more extreme drought events impacting farming and agricultural activities.

The extreme disaster events have increased impacts in this region. Drought confirms the drying trends, showing an increasing trend between 1951 and 2012. The recent trends in prolonged drought are observed more seriously. A slight increasing trend was observed for floods.

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APPENDIX

Additional details of the meteorological stations are given in Table A1.

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